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AIAA-87-1233
Turbulence Management by Active Wall for Fully Developed Two-Dimensional Boundary Layer

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AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference

June 8-10, 1987/Honolulu, Hawaii

TURBULENCE MANAGEMENT BY ACTIVE WALL FOR FULLY DEVELOPED TWO-DIMENSIONAL BOUNDARY LAYER

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ABSTRACT

Fully developed two-dimensional incompressible turbulent boundary layers in the presence of pressure gradient over moving wavy surfaces for the case of driven wall motion is studied numerically. The computted solution indicates strong interaction between the unsteady wave-induced flow and the time averaged mean flow at a certain discrete wavenumber for a given phase speed of the driven interface. Both favourable and adverse pressure gradient cases indicate skin friction reduction. However, for the adverse pressure gradient case, the interaction becomes stronger, tending to drastically reduce the skin friction and in certain rases, converged results are not obtained for high wavenumbers irrespective of their amplitudes. However, the present approach indicates a possible management of viscous drag in a qualitative way.

1. INTRODUCTION

Viscous drag reduction for flight vehicle and underwater vehicle is of current interest. The present paper deals with studies on a possible management technique for drag reduction for fully developed incompressible turbulent flow under favourable and adverse pressure gradients. The underlying surface considered is a two-dimensional progressive wavy wall. It has been shown[1] that an unsteady wall oscillation can change the phase of the oscillatory pressure to create an equivalent thrust instead of pressure drag. In a recent effort by Sengupta et al[2], it was conjectured that a compliant surface when externally driven modulates the pre-burst flow by providing a feed back pressure gradient comprising an excursion of favourable and adverse conditions. Following the idea of Benjamin[3], it was assumed that the presence of the wavy wall gives rise to organised oscillatory components of velocity and pressure. The equations describing the deviation of the flow field from the time mean were examined numerically to show the near-resonant interaction.

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In a computational work, Kuhn et al[4] have shown by large eddy simulation for channel flow, the existence of a spectral peak in streamwise velocity when the channel is driven externally in a sinusoidal form. Jang et al have also computed to show that turbulence scales and bursts are due to direct interaction between Orr-Sommerfeld mode and vertical vorticity mode. In the present study, resonance is shown to occur by distortion of the mean flow by Orr-Sommerfeld mode. Experimentally also, similar effects have been observed and the details are given in the paper by Sengupta et al[2].

The present study also indicates that when interaction takes place in a strong manner as in the case of flows with adverse pressure gradients, it is amplitude independent, thus demanding a nonlinear analysis. However, a qualitative picture arises from these studies.

2. GOVERNING EQUATIONS

The various assumptions and derivation of governing equations are given by Sengupta[1].

When the underlying surface executes unsteady motion, the resulting velocity and pressure field can be triply decomposed into a time mean, a periodic component and a random oscillation typical of turbulent flow, as given below:

$$q_i(\underset{\sim}{x},t) = Q_i(\underset{\sim}{x}) + \tilde{q}_i(\underset{\sim}{x},t) + q_i'(\underset{\sim}{x},t) \qquad (1)$$

where the first quantity on the right hand side is the time mean, the quantity with tilde denotes the periodic component and the last term denotes the random fluctuation. The mean flow is governed by the time-averaged boundary layer equation

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{R_e}\frac{\partial^2 u}{\partial y^2} - \frac{\partial}{\partial y}\overline{(u'v')} - \frac{\partial}{\partial y}\overline{(\tilde{u}\tilde{v})} \qquad (2)$$

In equation (2), the last term on the right hand side indicates the steady-streaming part of the wave-induced stress obtained from a solution of the governing equations set up for the oscillatory quantities, a simplified representation of which is as follows.

$$\dot{z}_i = \sum_{j=1}^{4} a_{ij} z_j + b_i$$

$$[z] = \left\{ \hat{u}, \frac{d\hat{u}}{dN}, \hat{v}, \hat{p} \right\}^T \tag{3}$$

where the quantities with caret represent the phase independent amplitude of the oscillatory flow quantities. Here, the oscillatory flow is described in a wave-following (S,N) coordinate system. The matrix a and the vector b are not only functions of the mean flow quantities but also depend on eddy viscosity and curvature terms associated with the coordinate transformation. A detailed discussion on the closure model is given by Sengupta et al[2].

3. SOLUTION PROCEDURE

Equation (2) is solved first with the last term on the right hand side set to zero. This mean flow solution is used in equation (3) and solved for disturbance quantities. The disturbance quantities obtained are used to compute the wave induced stresses (the last term on the right hand side of equation (2)) and once again the mean flow equation is solved. The solution obtained is again used to solve (3) and this procedure is repeated till the shear on the wall and inner layer converges to a prescribed limit of less than one percent change between successive iterations. The mean flow changes very rapidly near the wall for fully developed turbulent flow as compared to laminar flow and hence a large number of points are taken across the boundary layer, with the first point 0.00003 units away from the well. Disturbance flow equations are of the Orr-Sommerfeld type and because of their stiffness, orthonormalisations are resorted to. More details can be obtained from Sengupta[1].

4. RESULTS AND DISCUSSION

Computations have been carried out for flow over wavy surface for which the amplitude of the wave is 125 wall units. Reynolds number based on current length is 6.9 million and the shape factor is 1.35. The unit Reynolds number is 10 million. Figure I shows a schematic of the flow configuration.

Under a favourable pressure gradient. strong interactions begin to occur from the wave number of 96 onwards, as shown in Figure 2 where the skin friction of the wavy wall normalized with respect to that of an equivalent flat plate is shown plotted against the wavenumber. Results are shown for two phase speeds of $c = 0.4\,U_\infty$ and $c = 0.9\,U_\infty$. The corresponding variation of the wall pressure and the phase of the pressure are shown in Figures 3 and 4. At $c = 0.4\,U_\infty$, a 9 percent reduction in skin friction of the wavy wall is observed at K = 96 while at $c = 0.9\,U_\infty$, there is a 6 percent increase in the skin iriction at K = 105. The magnitudes and phases of wall pressure (Figures 3 and 4) do not indicate any large changes over the wavenumber range covered. Figure 5 shows the oscillatory shear normalised by mean shear for two phese speeds of $0.4\,U_\infty$ and $0.9\,U_\infty$ plotted against wavenumber.

Under the adverse pressure gradient, the skin friction of the wavy wall shows a drastic reduction of 12 percent at K = 68 and a further reduction at K = 75 when the phase speed is $0.4\,U_\infty$ as shown in Figure 6. However, just as with the favourable pressure gradient case, the magnitude and phase of the wall pressure do not show large changes (Figures 7 and 8). Oscillatory shear normalised by mean shear is plotted against wavenumber in Figure 9 for the adverse pressure gradient case.

In the present study, as the external modes have real phase speed and wavenumber, the depicted behaviour is indicative of interaction with lightly damped modes indicating drag reduction. For the favourable pressure gradient case, a wavenumber of 105 and phase speed of $0.90U_\infty$ indicates the presence of stable mode i.e., an increase in skin friction. In Figure 10, normalised skin friction of the wavy wall is plotted against wavenumber after the first iteration thereby indicating the corresponding linearised value for very small ratio of amplitude to wavelength (0.00026 Max.). The observation that the results show amplitude independence (Figure 10) suggests that the linearisation assumption limit of $\epsilon/\lambda = 0.02$ which was earlier arrived at by the ratio of oscillatory shear to mean shear may not be appropriate in the present case of strongly interacting flows. Also. from the Figures 5 & 9 one can see that the strong interaction is accompanied by increased oscillatory shear on the wall.

5. REFERENCES

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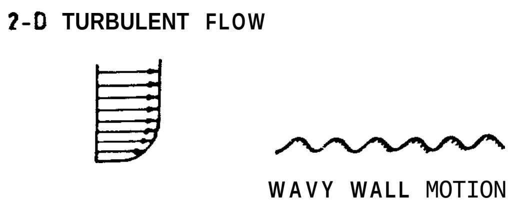


FIG. 1 A SCHEMATIC OF THE FLOW CONFIGURATION.

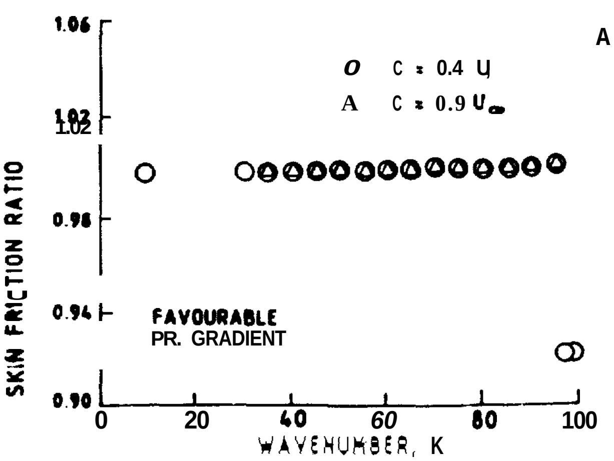


FIG. 2 VARIATION OF SKIN FRICTION WITH WAVENUMBER.

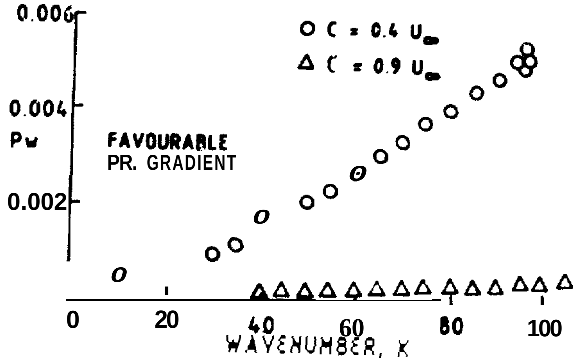


FIG. 3 VARIATION OF WALL PRESSURE WITH WAVENUMBER.

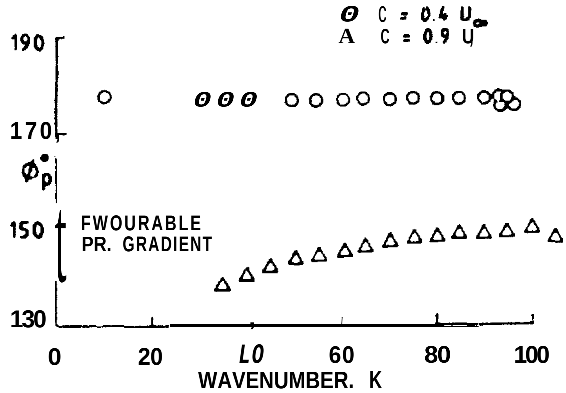


FIG. 4 VARIATION OF PHASE OF THE WALL PRESSURE WITH WAVENUMBER

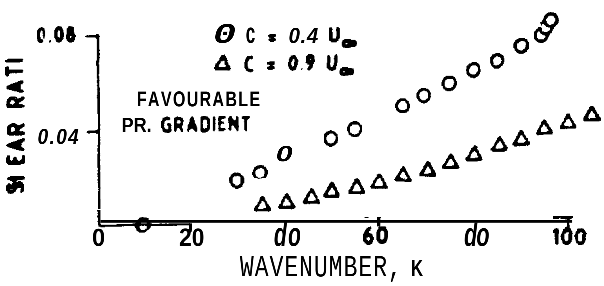


FIG. 5 VARIATION OF OSCILLATORY SHEAR WITH WAVENUMBER.

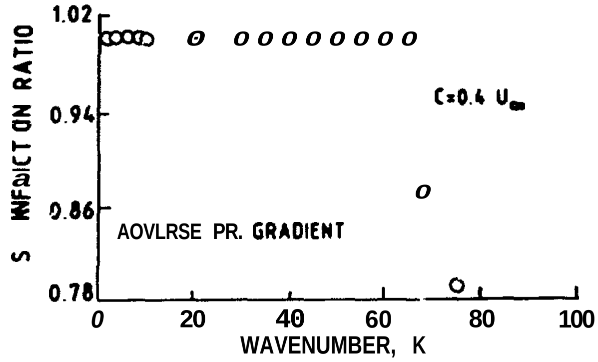


FIG.6 VARIATION OF SKIN FRICTION WITH WAVENUMBER.

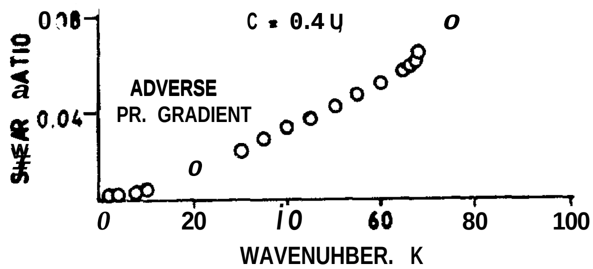


FIG. 9 VARIATION OF OSCILLATORY SHEAR WITH WAVENUMBER.

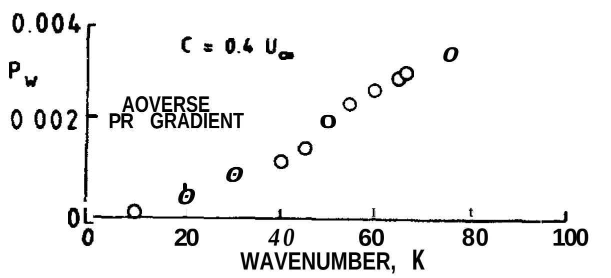


FIG. 7 VARIATION OF WALL PRESSURE WITH WAVENUMBER.

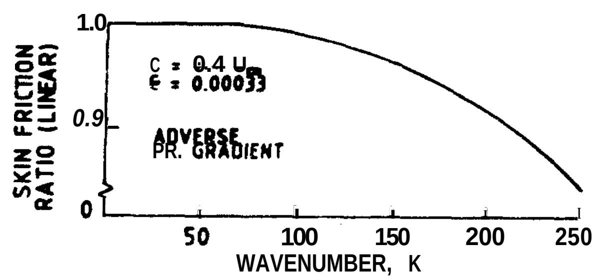
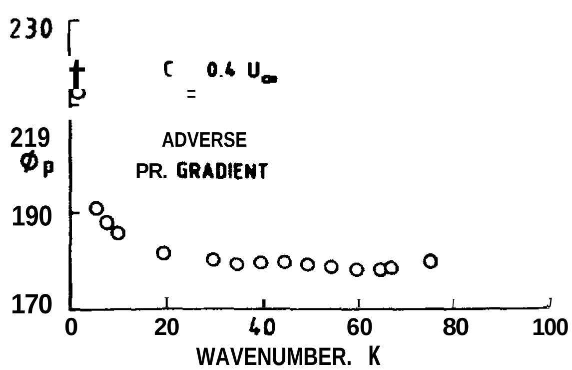


FIG. 10 VARIATION OF SKIN FRICTION RATIO (LINEAR) WITH WAVENUHBER.



FJG.8 VARIATION OF PHASE OF THE WALL PRESSURE WITH WA VENUMBER.

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